US011124281B2

(12) **United States Patent**
Aukes et al.

(10) **Patent No.: US 11,124,281 B2**
(45) **Date of Patent: Sep. 21, 2021**

(54) **MECHANISMS FOR STEERING ROBOTIC FISH**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 26 days.

(21) Appl. No.: **16/655,018**

(22) Filed: **Oct. 16, 2019**

(65) **Prior Publication Data**

US 2020/0115018 A1 Apr. 16, 2020

Related U.S. Application Data

(60) Provisional application No. 62/746,438, filed on Oct. 16, 2018.

(51) **Int. Cl.**
B63H 1/36 (2006.01)
B25J 9/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***B63H 1/36*** (2013.01); ***B25J 9/003*** (2013.01); ***B25J 11/00*** (2013.01); ***B63H 21/17*** (2013.01)

(58) **Field of Classification Search**
CPC .. B63H 1/36; B63H 21/17; B25J 9/003; B25J 11/00
See application file for complete search history.

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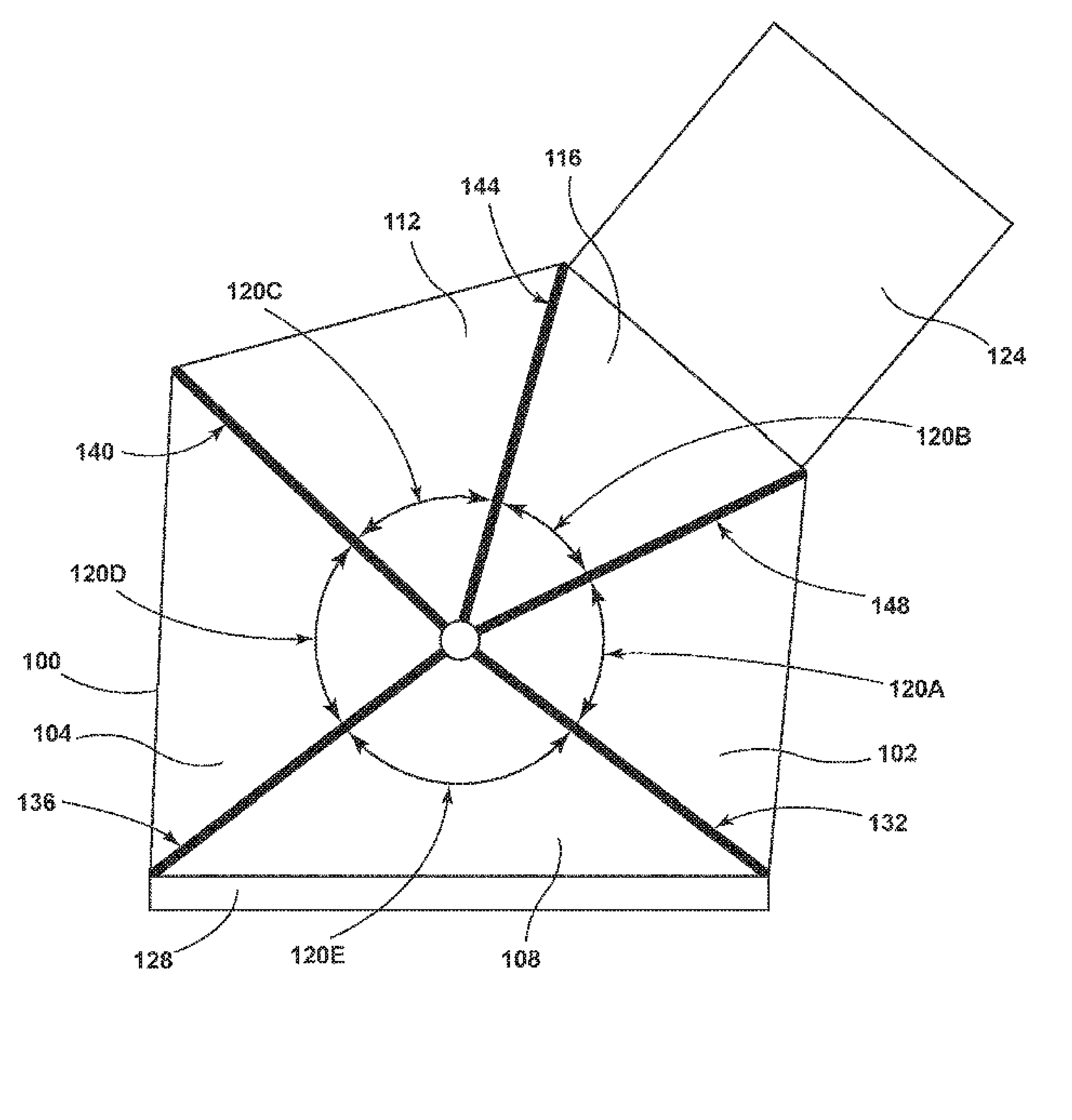
(57) **ABSTRACT**

In one aspect, a device for providing propulsion in water is provided by the present disclosure. The device includes a parallel mechanism including at least five rigid bars and at least five joints, each joint being positioned between two of the rigid bars and configured to allow movement of the at least five rigid bars, a first servo motor coupled to a first rigid bar included in the at least five rigid bars, a second servo motor coupled to a second rigid bar included in the at least five rigid bars, and a controller coupled to the first servo motor and the second servo motor and configured to actuate the first servo motor and the second servo motor according to a predetermined pattern.

20 Claims, 11 Drawing Sheets



(51) **Int. Cl.**
B63H 21/17 (2006.01)
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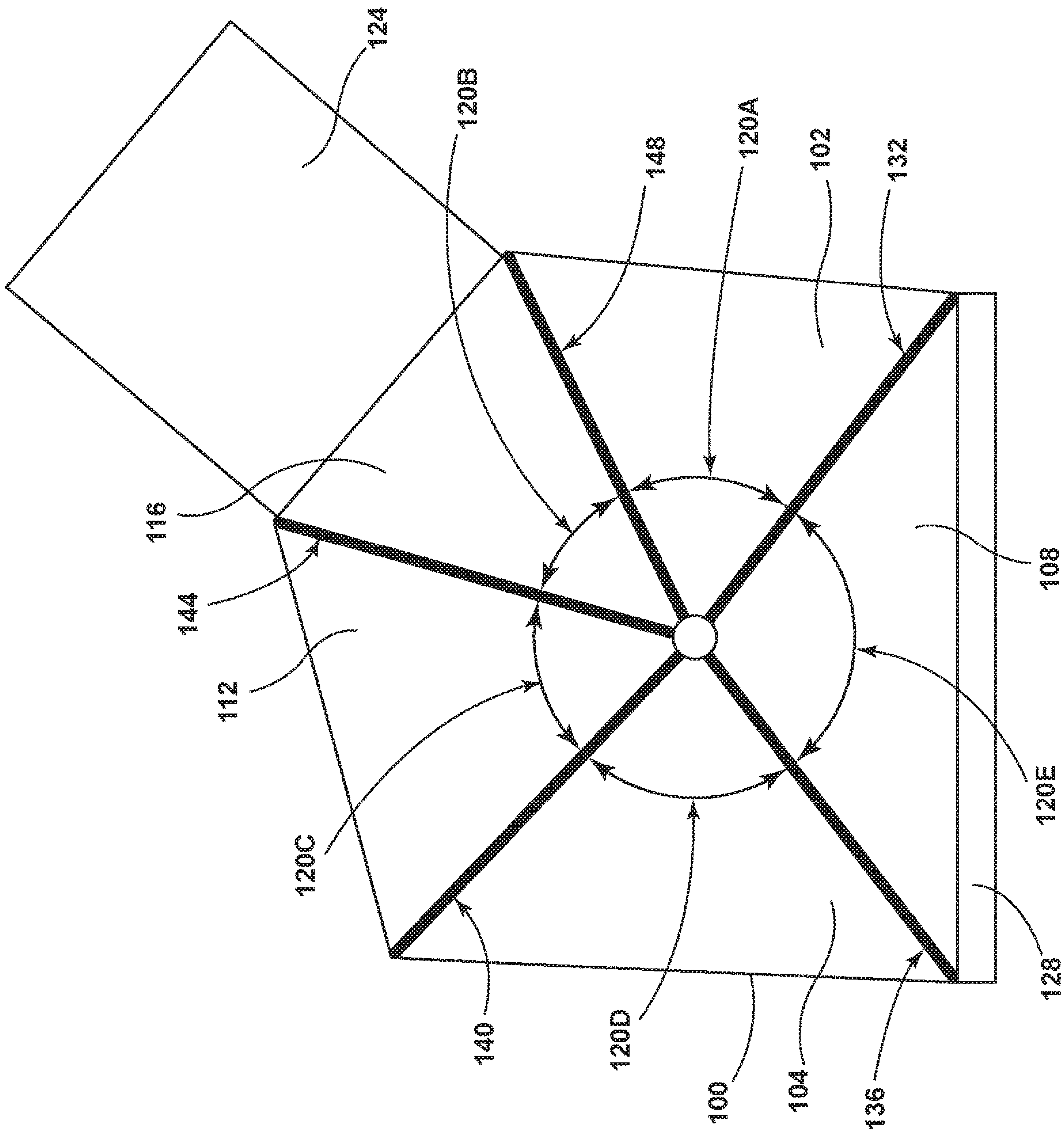
124
120B
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120A
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120E
120C
140
120D
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104
136
128

FIG. 1

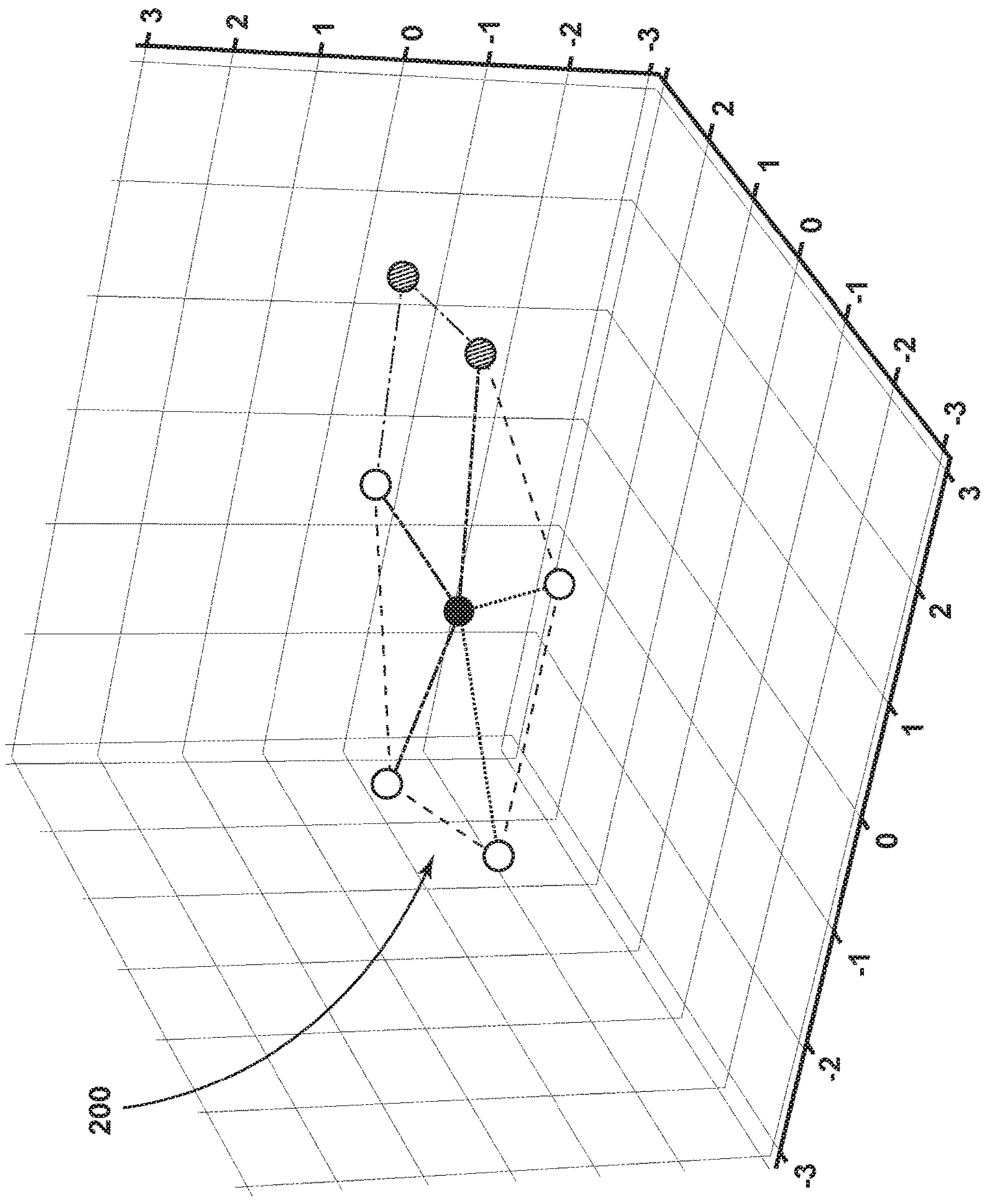


FIG. 2

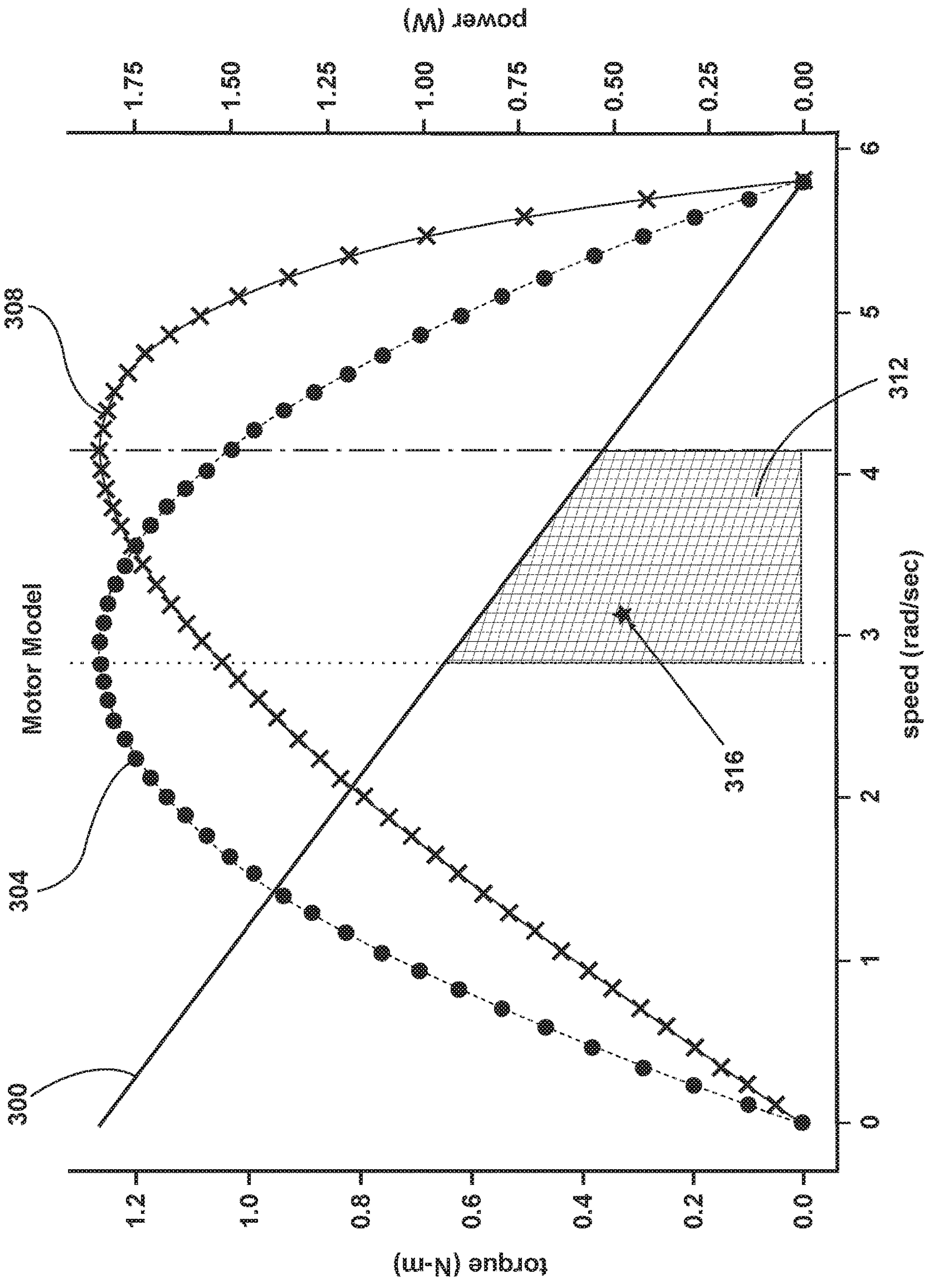

Motor Model
torque (N-m)
power (W)
speed (rad/sec)
300
304
308
312
316

FIG. 3

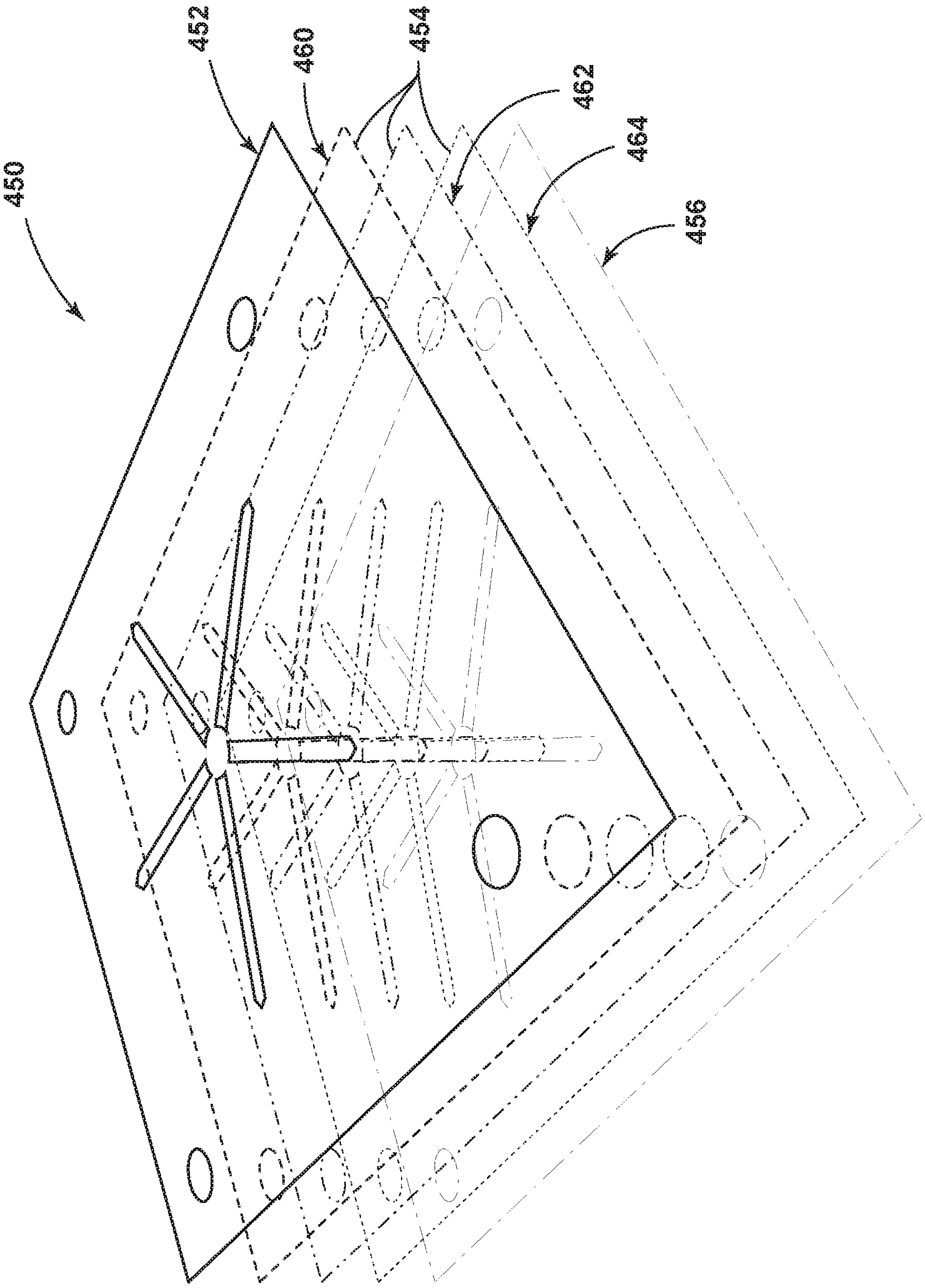


FIG. 4

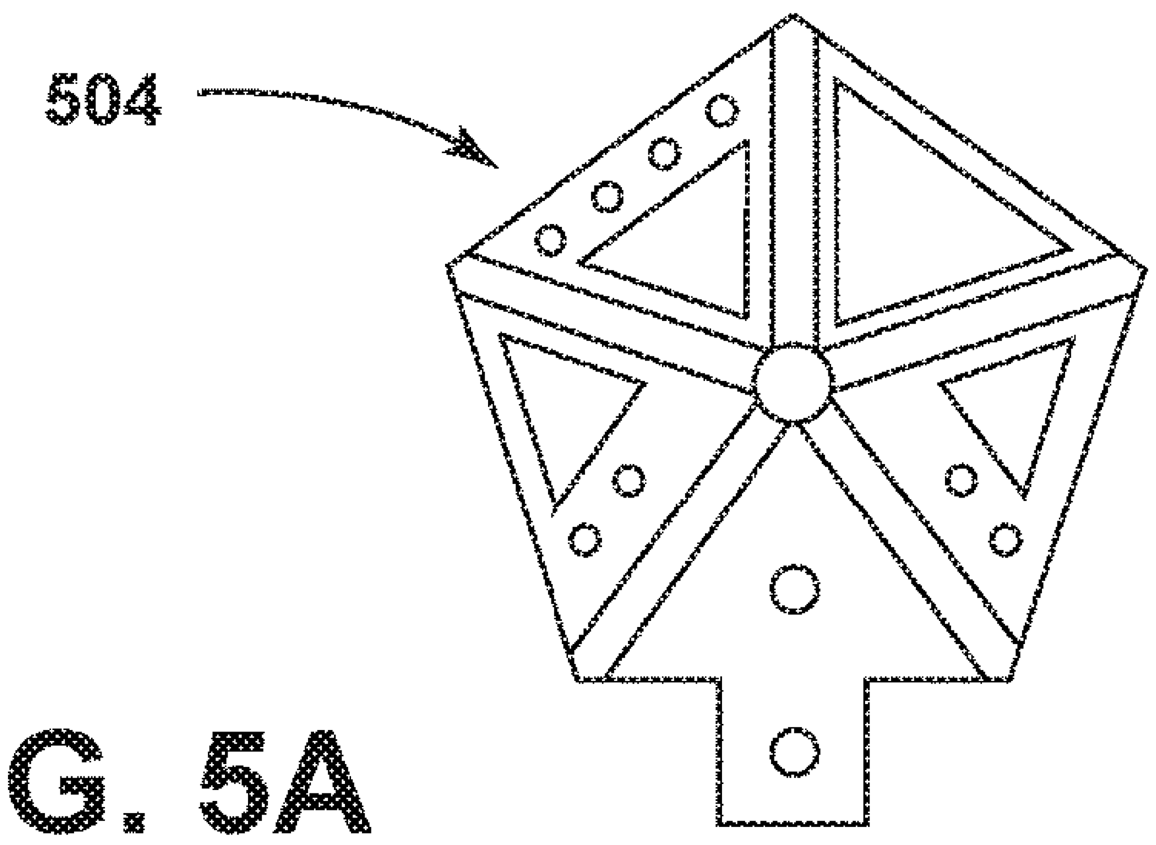


FIG. 5A

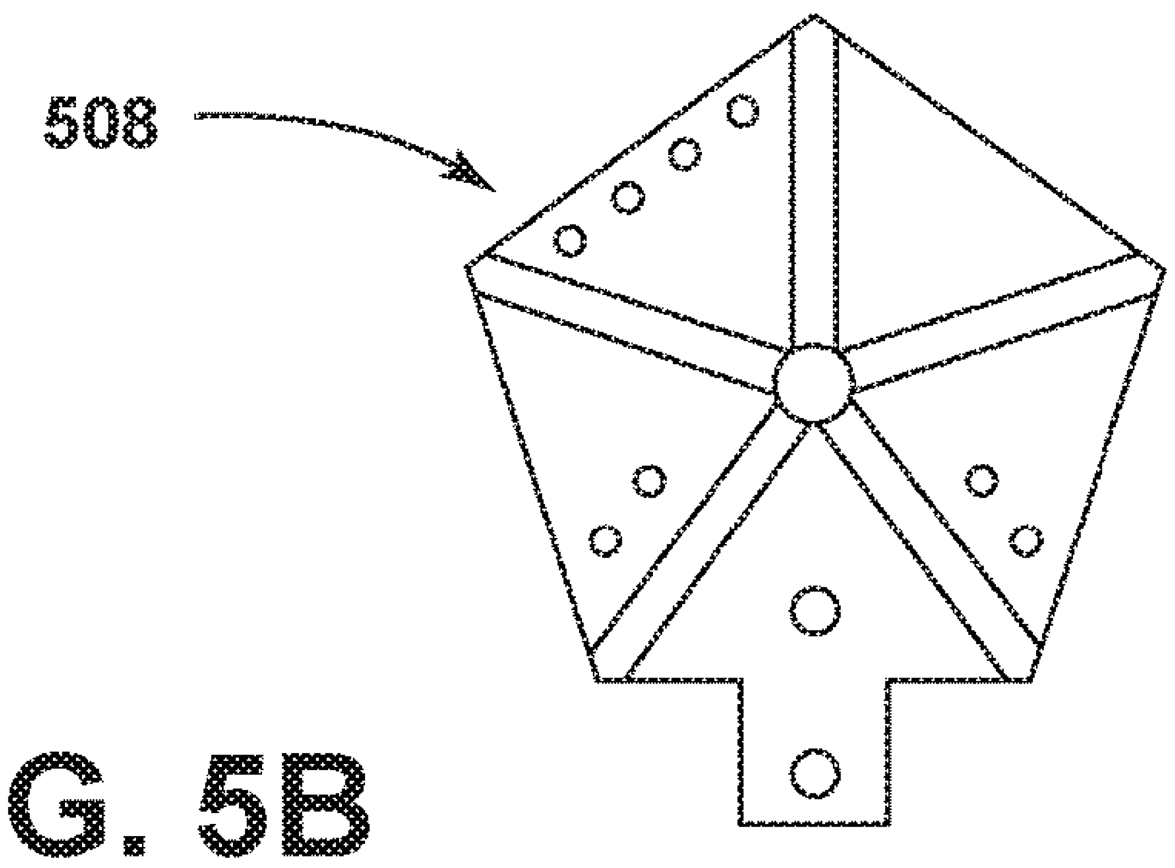


FIG. 5B

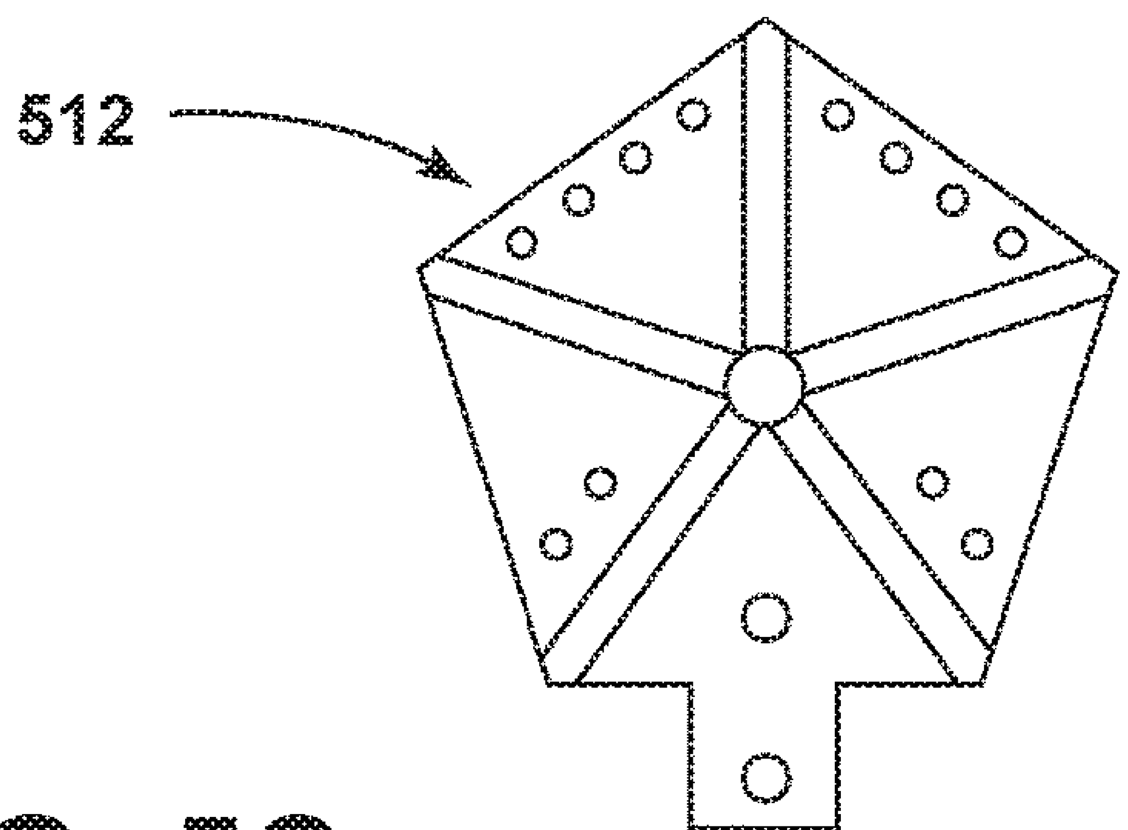


FIG. 5C

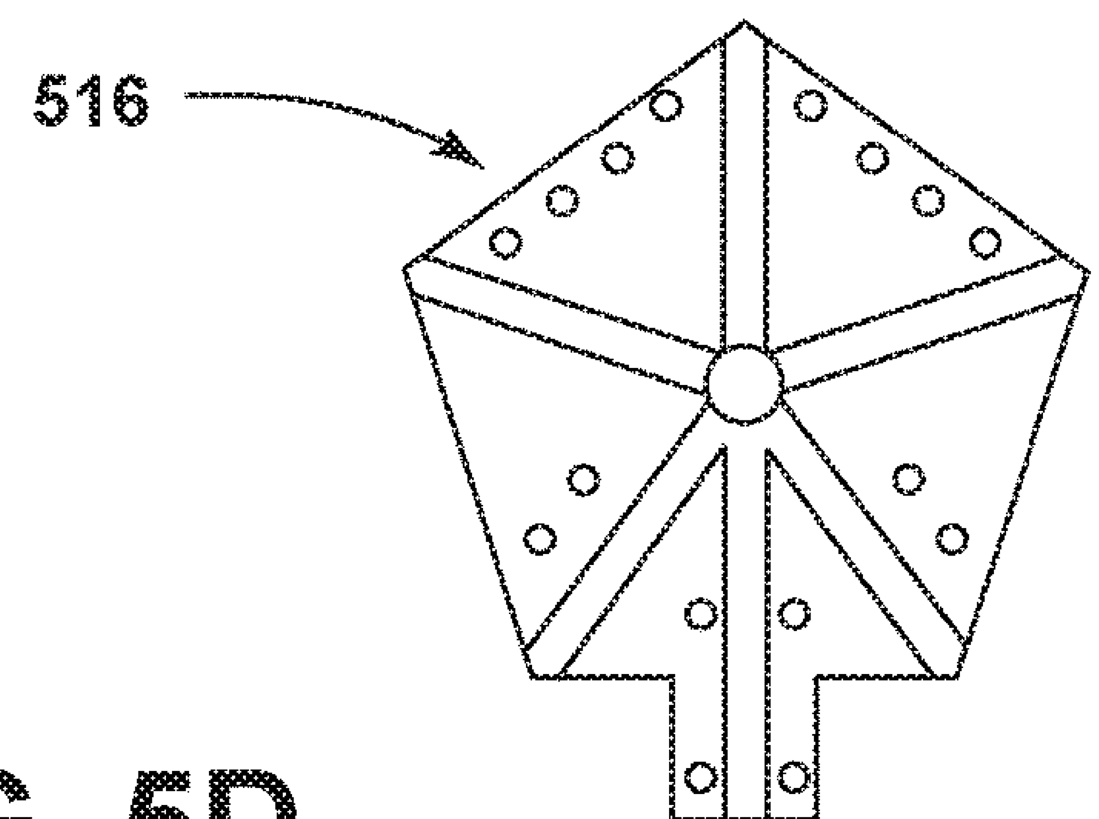


FIG. 5D

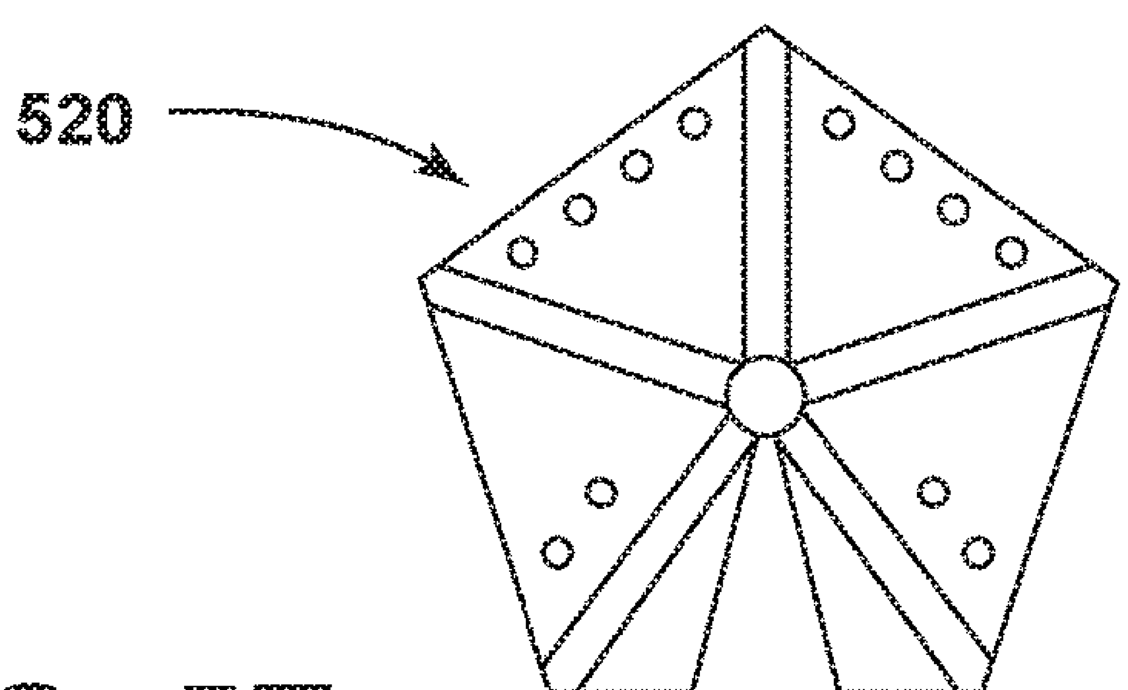


FIG. 5E

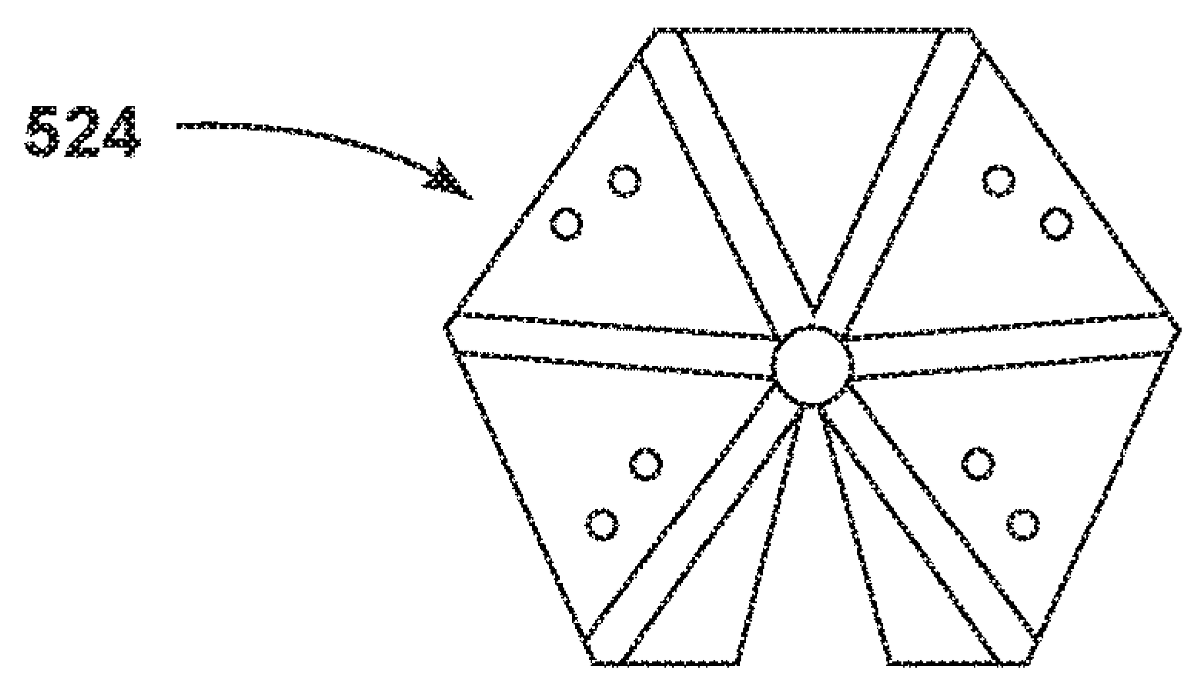


FIG. 5F

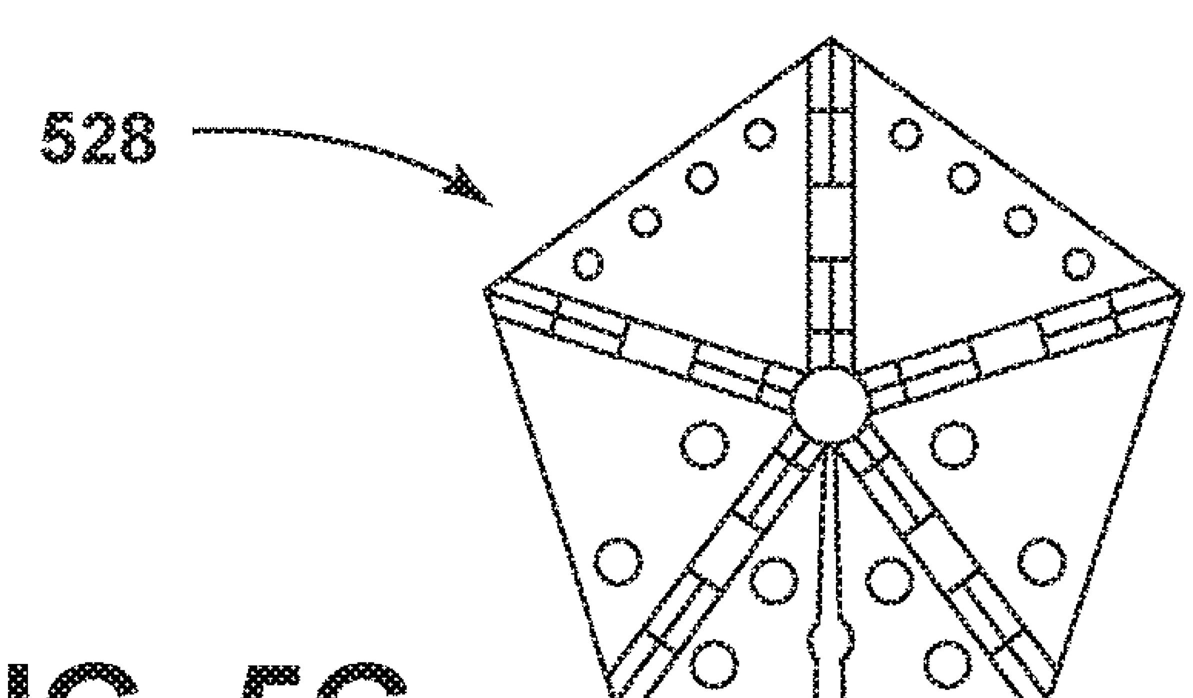


FIG. 5G

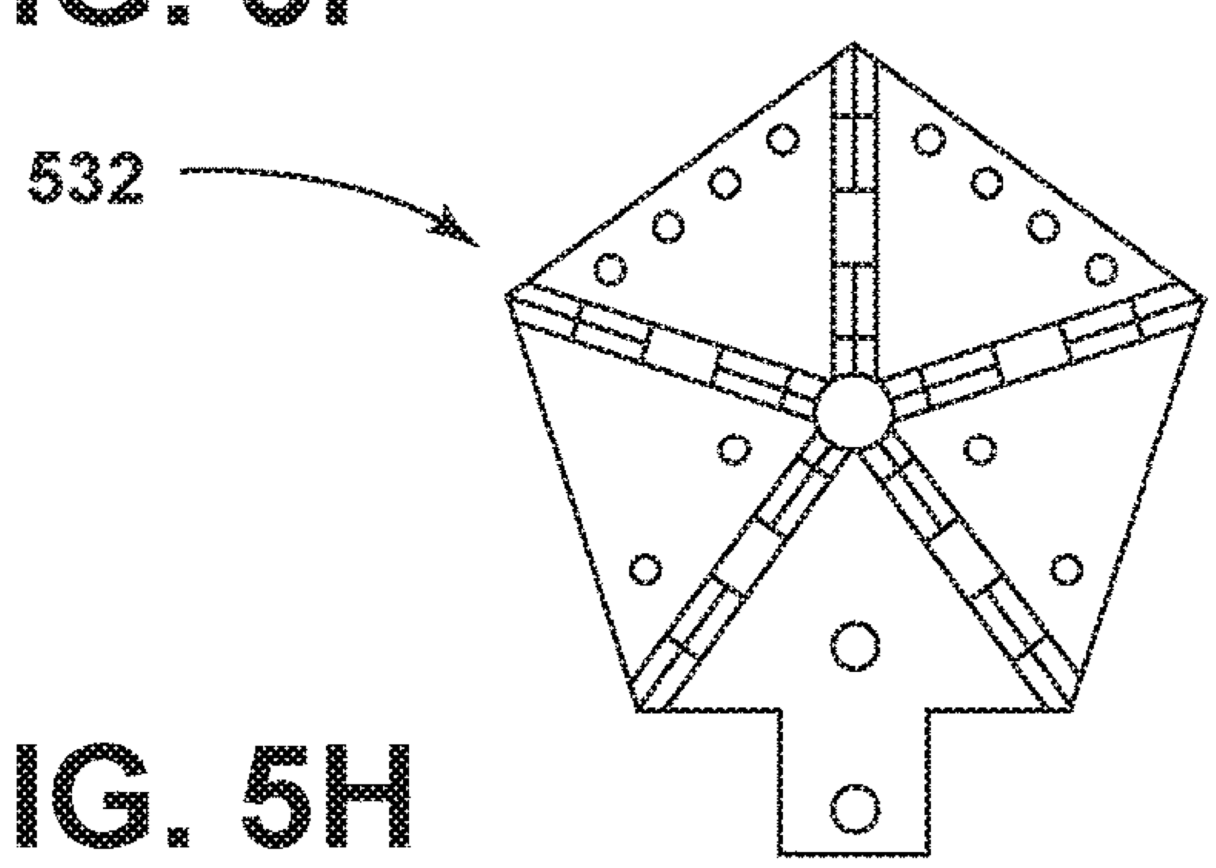


FIG. 5H

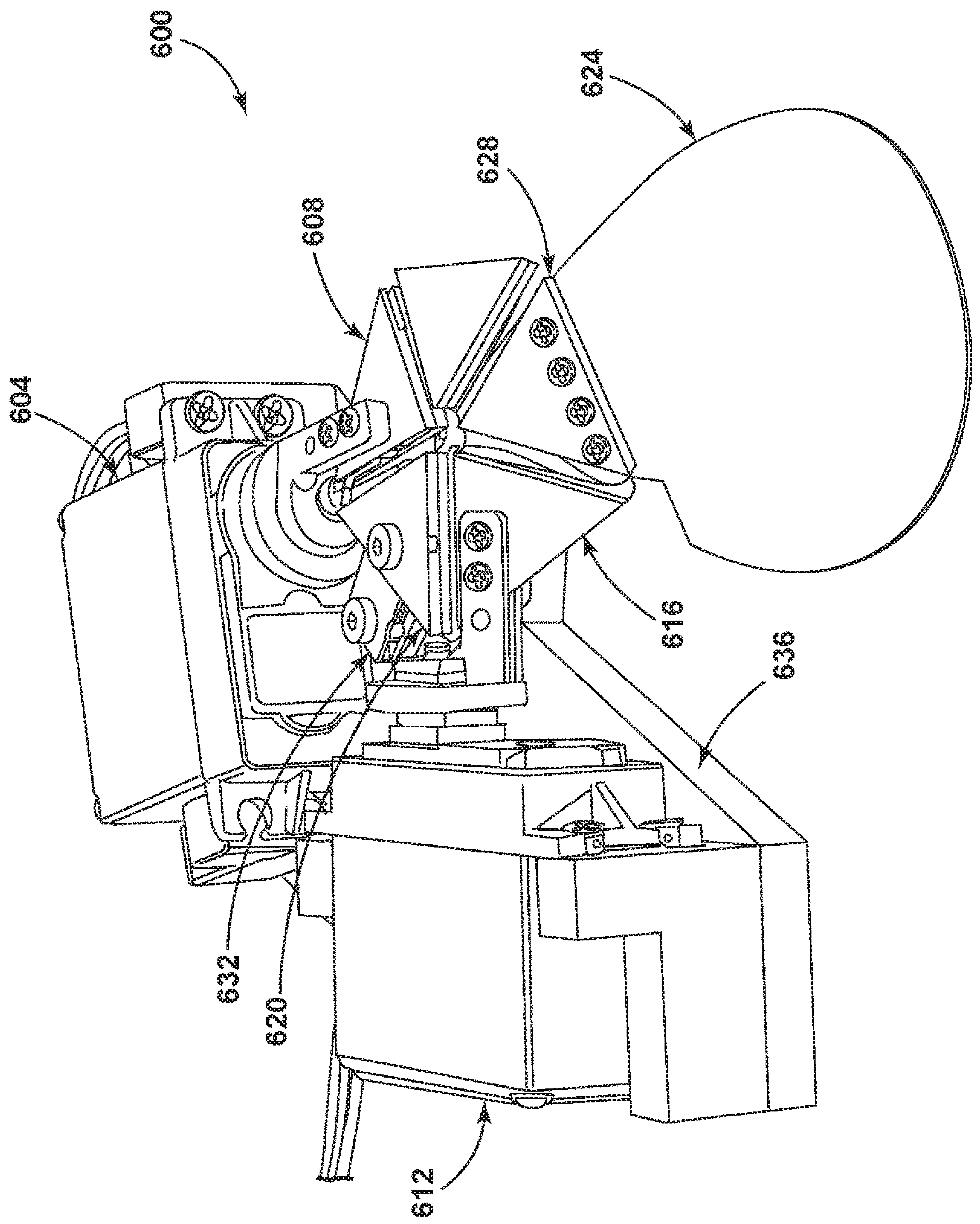


FIG. 6

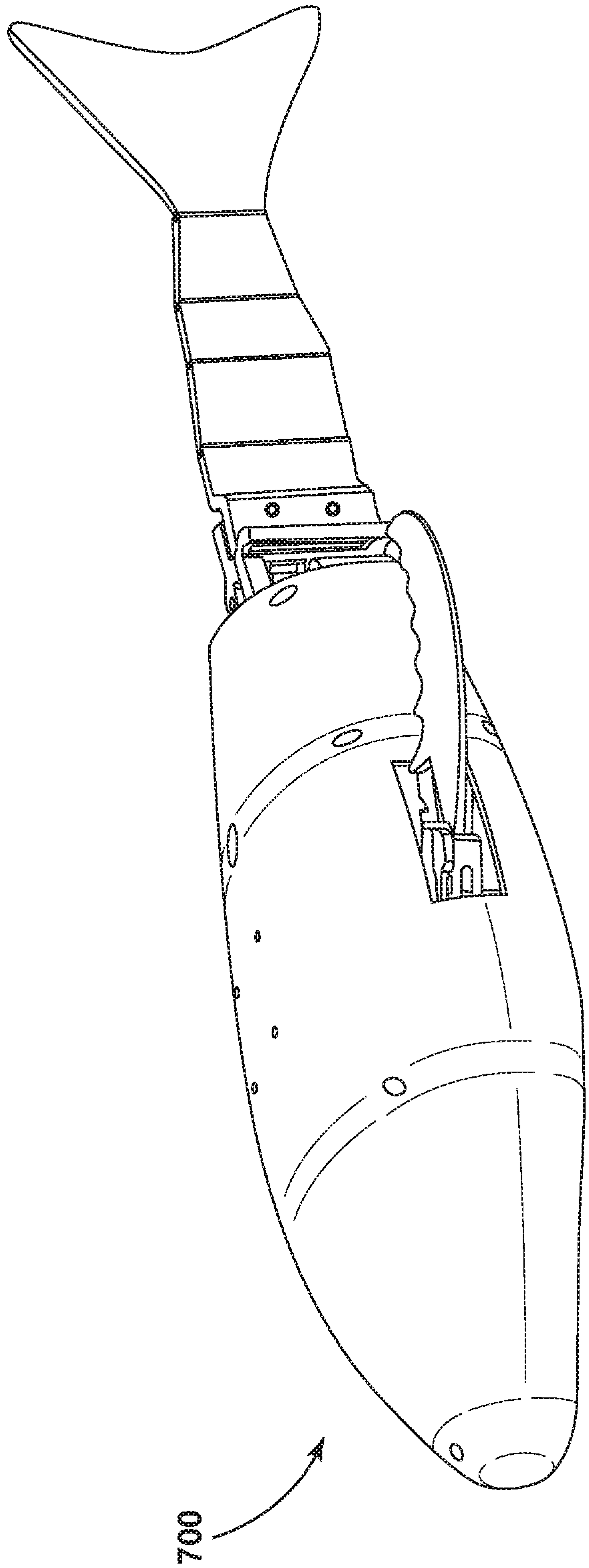


FIG. 7

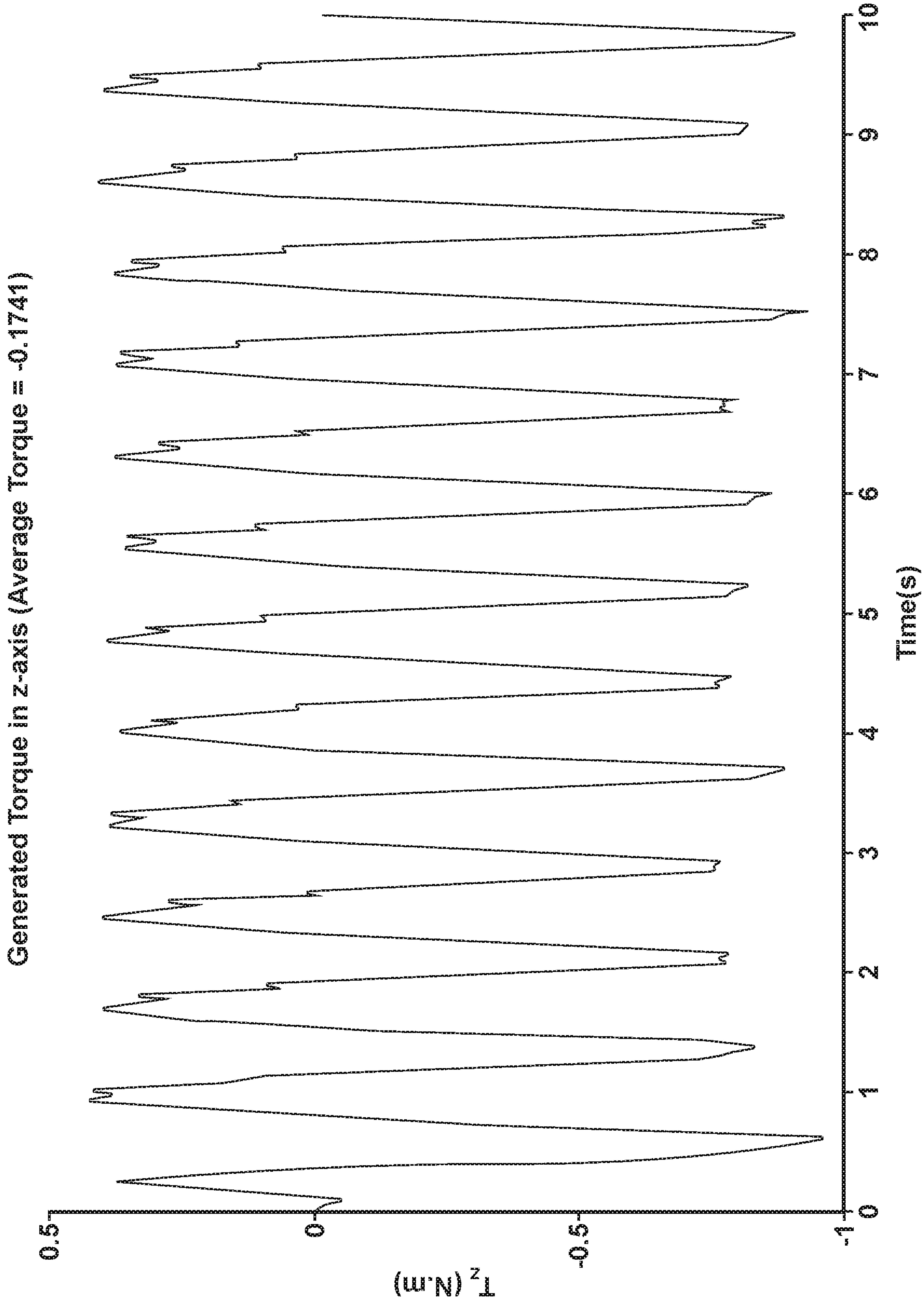

Generated Torque in z-axis (Average Torque = -0.1741)
T_z (N.m)
0.5
0
-0.5
-1
Time(s)
0
1
2
3
4
5
6
7
8
9
10

FIG. 8

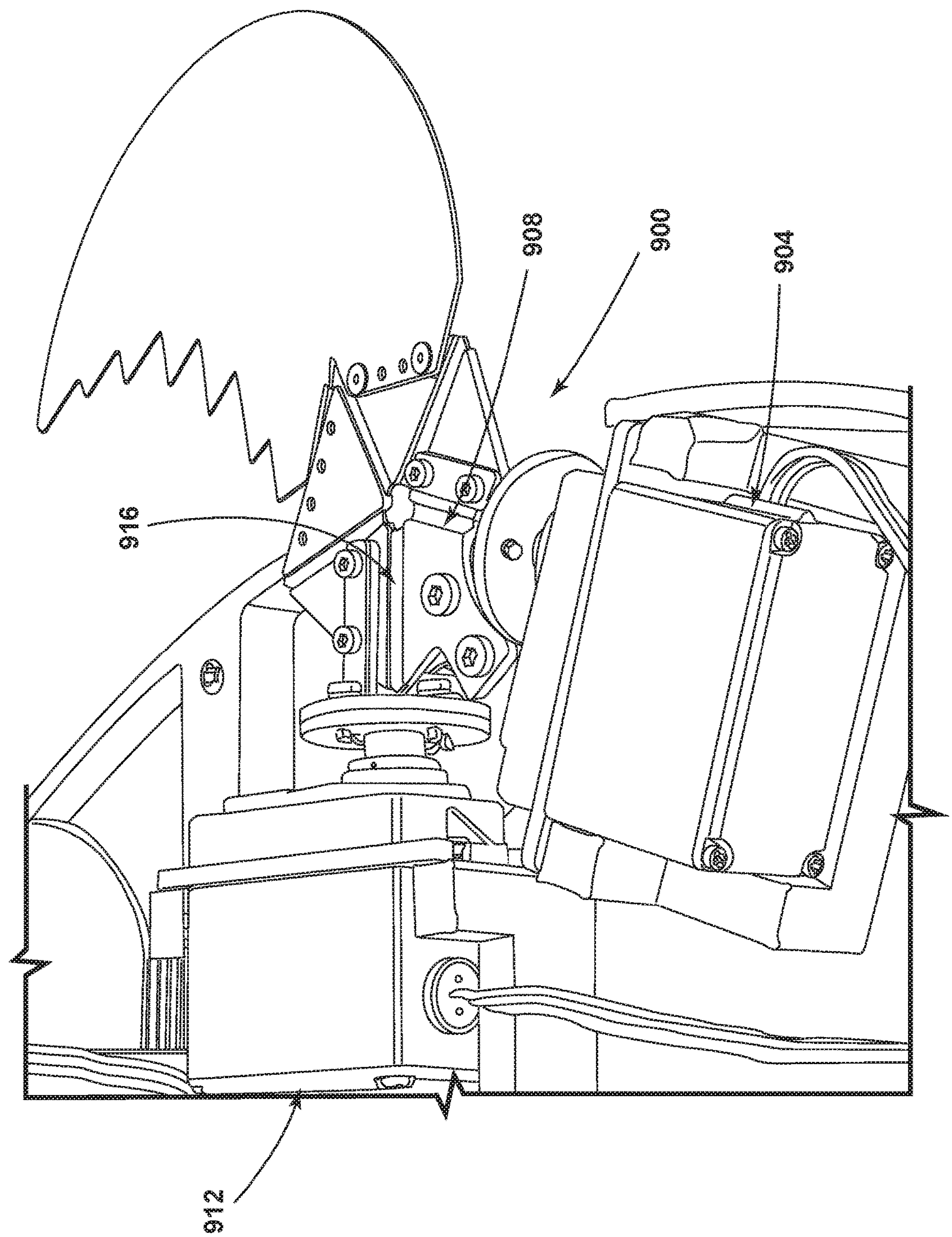
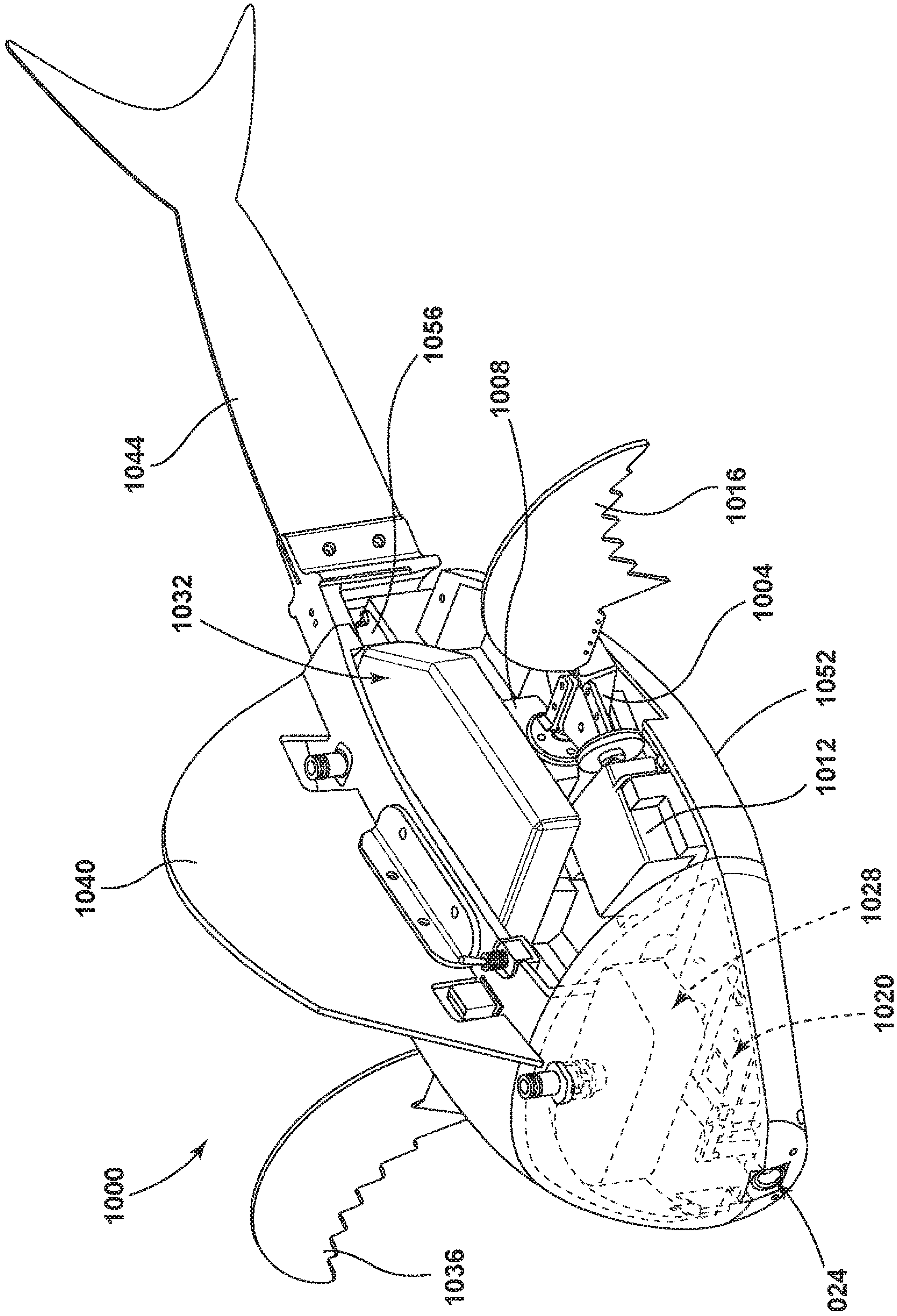


FIG. 9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1052
1056

FIG. 10

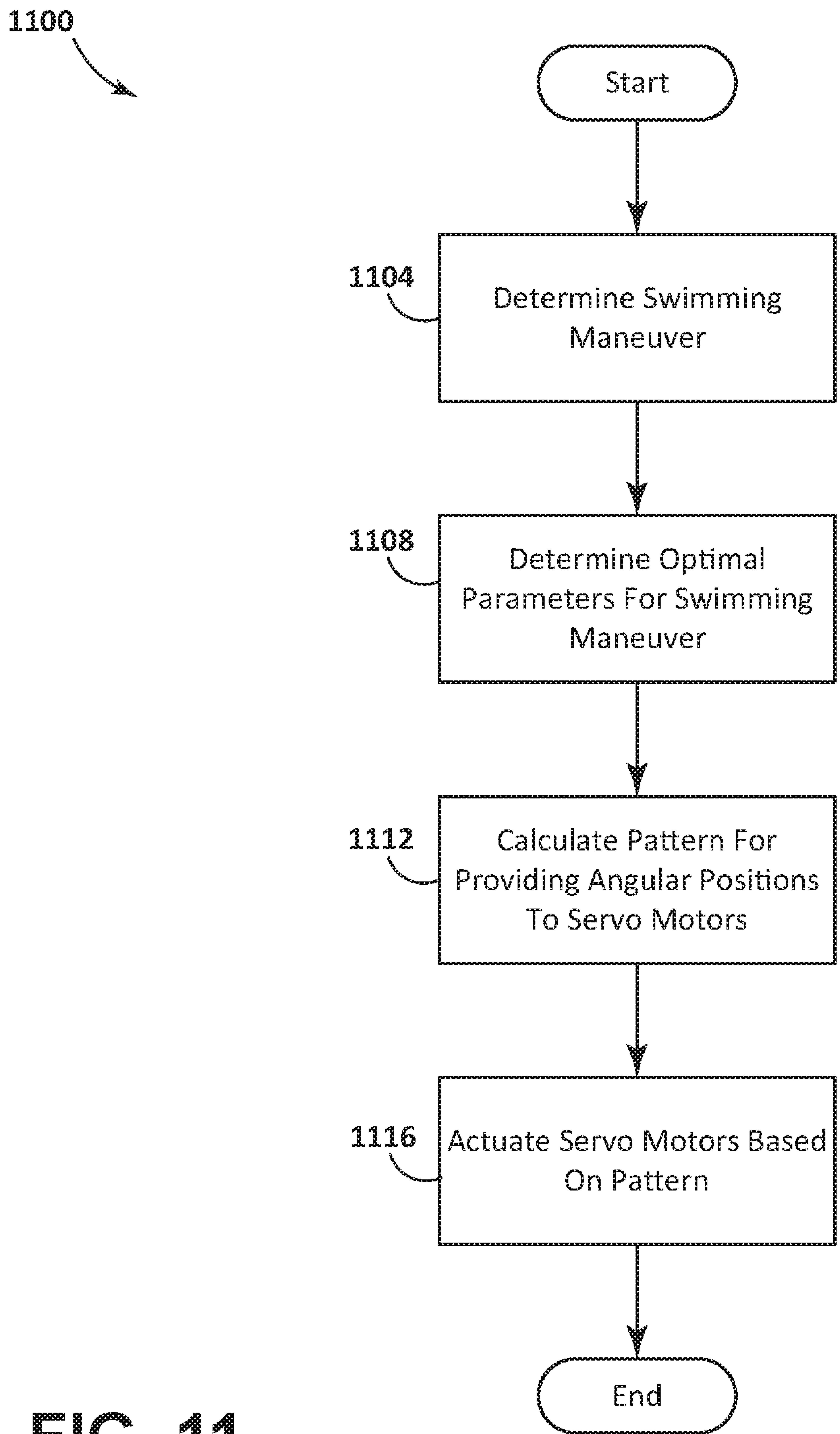
1100
Start
1104
Determine Swimming Maneuver
1108
Determine Optimal Parameters For Swimming Maneuver
1112
Calculate Pattern For Providing Angular Positions To Servo Motors
1116
Actuate Servo Motors Based On Pattern
End

FIG. 11

MECHANISMS FOR STEERING ROBOTIC FISH

This application is based on, claims priority to, and incorporates herein by reference in its entirety, U.S. Provisional Application No. 62/746,438, filed Oct. 16, 2018, and entitled "Mechanisms For Steering Robotic Fish."

BACKGROUND

Algae and other unwanted plant growth is a growing problem in many bodies of water throughout the world. A robotic fish capable of clearing this growth is envisioned. In order to make the robotic fish viable, an effective, low cost propulsion system is required. Prior methods have utilized bio-inspired examples as a basis for robotic propulsion. Methods for steering the robotic fish may utilize a robotic tail caudal fin, primarily for locomotion, and one or more robotic pectoral fins for steering and maneuvering. However, previous methods of robotically modeling a pectoral fin have had drawbacks of low performance or high cost.

One prior example of a robotic pectoral fin design from the University of Science and Technology of China utilized eight servo motors, each attached to an active bar made from a rigid material. The design was based on a Blue Spotted Ray. The rigid bars were attached to a thin latex sheet. The fin then steered a robotic fish by actuating the servo motors. However, this design is expensive, as it utilizes eight servo motors per pectoral fin. Current solutions typically do not permit multiple rotational degrees of freedom within a single fin, or require a complex mechanical linkage facilitated by precision-machined parts.

A device that effectively steers and maneuvers a robotic fish at an affordable cost is therefore desired.

SUMMARY

Systems and methods of a robotic fish device that uses an improved pectoral fin device to efficiently steer and maneuver a robotic fish at an affordable cost are described herein. In one aspect, a device for providing propulsion in water is provided by the present disclosure. The device includes a parallel mechanism including at least five rigid bars and at least five joints, each joint being positioned between two of the rigid bars and configured to allow movement of the at least five rigid bars, a first servo motor coupled to a first rigid bar included in the at least five rigid bars, a second servo motor coupled to a second rigid bar included in the at least five rigid bars, and a controller coupled to the first servo motor and the second servo motor and configured to actuate the first servo motor and the second servo motor according to a predetermined pattern.

In the device, the at least five joints can be evenly spaced around the parallel mechanism.

In the device, the at least five joints can include a fabric.

In the device, the predetermined pattern can include a sinusoidal pattern.

In the device, a third rigid bar included in the at least five rigid bars can be coupled to a substrate, the third rigid bar being positioned between the first rigid bar and the second rigid bar, and the first servo motor and the second servo motor can be coupled to the substrate.

In the device, the third rigid bar can be attached to the substrate via a structural member.

The device can further include a fin attached to a fourth bar of the at least five rigid bars and extending orthogonally away from the parallel mechanism, the fourth bar positioned adjacent to the first rigid bar, and the fourth bar moving when the first rigid bar moves.

In the device, the pattern can be determined based on predetermined parameters corresponding to a swimming maneuver, and the predetermined pattern can include a series of angular positions for the first servo motor and the second servo motor.

The device can be included in a robotic fish.

In the device, the at least five joints can include nylon.

The device can further include a fin coupled to a third rigid bar included in the at least five rigid bars. The fin can be configured to provide a turning force to a submersible robot. The fin can be configured to provide a locomotion force to a submersible robot.

In another aspect, a robotic fish is provided by the present disclosure. The robotic fish includes a parallel mechanism comprising at least five rigid bars, a first servo motor coupled to a first rigid bar included in the at least five rigid bars, a second servo motor coupled to a second rigid bar included in the at least five rigid bars, a fin coupled to a third rigid bar included in the at least five rigid bars; and a controller coupled to the first servo motor and the second servo motor and configured to actuate the first servo motor and the second servo motor according to a predetermined pattern in order to provide a turning force to the robotic fish.

In the robotic fish, the parallel mechanism can include at least five joints, each joint being positioned between two of the rigid bars and configured to allow movement of the at least five rigid bars. The at least five joints can be evenly spaced around the parallel mechanism. The at least five joints can include a fabric.

In the robotic fish, the predetermined pattern can include a sinusoidal pattern.

The robotic fish can further include a caudal fin coupled to a third servo motor, and the controller can be further coupled to the third servo motor and configured to actuate the third servo motor in a second predetermined pattern in order to provide a locomotion force to the robotic fish.

In the robotic fish, the fin can extend orthogonally away from the parallel mechanism.

The present disclosure provides devices and methods that use two motors, such as servo motors, and a two Degrees of Freedom (DOF) parallel mechanism to steer a robotic fish. In particular, the parallel mechanism accurately mimics the rotational movement of a fish's pectoral fin. The two degrees of freedom refer to two active bars of the mechanism. These bars may be actuated by an actuator such as a motor, pneumatic piston, hydraulic piston, or other actuation methods known in the art. The mechanism may have one or more passive bars. For example, a 5-bar mechanism may have two active and three passive bars. One or more hinge layers may be interposed between the bars. The hinge layer allows all the bars to move as a result of actuation of the active bars. A fin may be attached to the parallel mechanism. The fin may be attached to a passive joint. The actuators may be controlled by a controller configured to move the actuators in a pattern that allows the mechanism and/or fin to mimic the motion of a fish's pectoral fin. This device allows a robotic fish to be steered.

The laminate fabrication process described in this disclosure permits multiple degrees of freedom with a less expensive fabrication process that produces multiple rotational degrees of freedom. This permits the pectoral fin to rotate about multiple axes simultaneously to (potentially) create more complex swimming motions such as turning, diving, and forward swimming.

The foregoing and other advantages of the invention will appear from the following description. In the description, reference is made to the accompanying drawings, which form a part hereof, and in which there is shown by way of illustration a preferred embodiment of the invention. Such embodiment does not necessarily represent the full scope of the invention, however, and reference is made therefore to the claims and herein for interpreting the scope of the invention.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a diagram of a five-bar parallel mechanism in accordance with the present disclosure.

FIG. **2** is a model of a 5-bar mechanism, with a focal point added.

FIG. **3** is a motor model graph.

FIG. **4** is a diagram of manufacture layers of an example 5-bar mechanism.

FIG. **5**A is a mechanism with five bars, one fin attachment and a plurality of water holes.

FIG. **5**B shows a mechanism with five bars and one fin attachment.

FIG. **5**C shows a mechanism with five bars and two fin attachments.

FIG. **5**D shows a mechanism with six bars and two fin attachments.

FIG. **5**E shows a mechanism with five bars and an extra angle.

FIG. **5**F shows a mechanism with six bars and an extra angle.

FIG. **5**G shows a mechanism with six bars, an extra angle, and supported hinges.

FIG. **5**H shows a mechanism with five bars and supported hinges.

FIG. **6** is a top perspective view of an example embodiment of a pectoral fin device.

FIG. **7** is a side perspective view of an example robotic fish having a pectoral fin device in accordance with the present disclosure.

FIG. **8** is a graph of exemplary data of collected torque values from an experiment.

FIG. **9** is a top perspective view of an example servo horn attached to a servo motor.

FIG. **10** is an exemplary robotic fish.

FIG. **11** is a process for controlling actuators coupled to parallel mechanisms and/or caudal fins in a robotic fish.

DETAILED DESCRIPTION

In one aspect, the present disclosure provides a device including a parallel mechanism, a first actuator, a second actuator, a fin, and a controller. The parallel mechanism comprises a first rigid layer, a hinge layer, a second rigid layer, two active bars, and a plurality of passive bars. The first actuator is attached to a first active bar of the parallel mechanism. The second actuator is attached to a second active bar of the parallel mechanism. The controller is configured to move the actuators in a pattern that allows the parallel mechanism and/or fin to mimic the motion of a fish's pectoral fin.

Embodiments of systems, devices, and methods in accordance with the present disclosure provide a device using two actuators, and a two Degrees of Freedom (DOF) parallel mechanism to steer a robotic fish. In particular, the parallel mechanism accurately mimics the rotational movement of a fish's pectoral fin. An exemplary embodiment of a steering device for a robotic fish includes two servo motors and a parallel mechanism with two active bars. The two active bars may be actuated individually by one of the servo motors. The parallel mechanism may be attached to a fin such as a pectoral or side fin in order to apply a force created by the mechanism to the fin in order to propel and/or steer the robotic fish. The parallel mechanism used in conjunction with the side fin may be used with an opposing side fin as well as in conjunction with a tail fin to create natural-looking swimming motion similar to how a fish swims. The additional degrees of freedom provided by this joint can permit the fish to maneuver in novel ways that other fish robots have not yet demonstrated.

Referring now to FIG. **1**, an exemplary five-bar rotational mechanism **100** mimics the rotational movement of fish's pectoral fin. The exemplary mechanism **100** is a 2 Degrees of Freedom (DOF) parallel mechanism that consists of a five bars loop with two active bars including a first active bar **102** and a second active bar **104** and three passive bars including a first passive bar **108**, a second passive bar **112**, and a third passive bar **116**. A design parameter of the mechanism is the angle between each hinge (θ_i) as indicated by angles **120**A-E. The angle between each hinge can be the angle between the centerline of each hinge. A fin **124** can be coupled to the five-bar rotational mechanism **100**. More specifically, the fin **124** can be coupled to two bars such as the second passive bar **112** and the third passive bar **116**. The five-bar rotational mechanism **100** can include a first active joint **132**, a second active joint **136**, a first passive joint **140**, a second passive joint **144**, and a third passive joint. The first active joint **132** can be connected to the first active bar **102** and the first passive bar **108**, which may also be referred to as a ground bar. The second active joint **136** can be connected to the second active bar **104** and the first passive bar **108**. The first passive joint **140** can be connected to the second active bar **104** and the second passive bar **112**. The second passive joint **144** can be connected to the third passive bar **116** and the second passive bar **112**. The third passive joint **148** can be connected to the third passive bar **116** and the first active bar **102**.

The joints can be a flexible material that allows the bars, which can be include rigid materials, to move relative to the other bars. The active bars **102** and **104** can each be coupled to an actuator (not shown) such as a servo motor and actuated as will be explained below. The first passive bar **108** can be coupled to a substrate **128** such as a fish body and fixed in place. The substrate is a component of a device being propelled by the five bar mechanism **100**, such as a submersible robot such as a robotic fish. The active bars **102** and **104** can then move and affect the movement of the fin **124**, as will be explained below.

In order to simulate the motion of an exemplary five bar mechanism with joints evenly spaced around the five bar mechanism with symmetric 72 degree angles in-between (e.g. 72 degrees at the angles **120**A-E), a script such as a python script may be used. In this script, the position of the two fixed joints (e.g., the active joints **132**, **136**) which form the ground bar (e.g., passive bar **108**) and the angles between joints are defined. Furthermore, the angle between ground bar **108** and the two active bars **102**, **104** in an array of step iteration can be defined. An optimization method can be used to find the configuration of five-bar mechanism which match the current step angles. During this calculation process, all the other bars' angles will be obtained and if the optimization error is within an acceptable level of margin, the configuration will be considered as a result. The script can simulate the work space of the mechanism **100** when both of the active bars' angles are changing from −175 degrees to +175 degrees.

Jacobian calculations can be used to find an output path of a fin of a fish from the data generated by mapping the reference points. In the case of a Bluegill, an output path that is sinusoidal is needed to accurately mimic the Bluegill pectoral fin motion.

Elements of an exemplary five bar mechanism can be coded in a script to determine if the mechanism is capable of producing a sinusoidal output path of motion. These elements are the constraints that defined each of the five vectors that made up the five-bar mechanism. After defining all five vectors, the program was run through a series of angles to determine the points at each input angle. The program indicated that the mechanism is capable of producing a sinusoidal output path of motion.

Referring now to FIG. **2**, the five bar mechanism **200** with symmetric 72 degree angles between each joint was recreated in a modeling program with focal point added for a study of forces and velocities generated by the mechanism. An addition of a focal point of study was added to the existing Jacobian study of the five bar mechanism. Information about masses and gravity can be defined so the force vectors in the X, Y, and Z direction can be calculated. Then a script can run through a series of angle of motion to determine the torque the exemplary system would expect to experience. In this five bar mechanism, it was found that the expected torque each of the hinge motors would encounter would be 0.0395 Nm. The velocities of the motors of the system can then be found by using the power that the Bluegill pectoral fin uses 16.5 W/kg and the calculated torque. In this embodiment, the exemplary system should expect an average velocity of 2.87 m/s. This data can be used to determine an appropriate motor for the system.

Referring now to FIG. **3**, a motor model graph with a Speed-Torque curve **300**, a Mechanical Power curve **304**, and a Motor Efficiency curve **308** for a HiTec servo #HS-5646WP motor is shown. To analyze if a servo motor is appropriate for a parallel mechanism, technical information regarding the motor can be used in conjunction with the previously determined torque and velocity information to do analytic analysis. Using a motor's specifications on angular velocity, stall torque, and current draw, three graphs can be calculated using methods known in the art. These three graphs are speed-torque, mechanical power, and motor efficiency graphs. These three graphs form a region of optimal performance for the motor which is a gridiron area **312** of the graph in FIG. **3**. A star **316** within the gridiron region **312** of the graph is the maximum torque/speed that was previously determined that a certain system would be needing. If the system predicted requirements fall within the gridiron region **312** for the proposed motor, then the motor may be appropriate for the parallel mechanism. For example, a HiTec servo number HS-5646WP may be used for the exemplary parallel mechanism with symmetric 72 degree angles between each joint.

Referring now to FIG. **4**, an exemplary 5-bar mechanism **450** is shown. The 5-bar mechanism **450** may have a plurality of layers. In one embodiment, there may be a 5-bar mechanism **450** with three layers. A first layer **452** may be a rigid layer. A second layer **454** may be a hinge layer. A third layer **456** may be a rigid layer. The rigid layers **452**, **456** may be composed of acrylic, fiberglass, or any other rigid material suitable for use in water. The rigid layers **452**, **456** may have hinge lines cut at predetermined angles. The hinge layer **454** may be composed of one or more layers of materials that are flexible enough to function as a hinge between bars and/or are relatively waterproof. In some embodiments, the hinges may be made from a three layer composition including a fabric layer **460**, a polyester layer **462**, and another fabric layer **464** of the same or different fabric, to increase the durability of the hinge. The fabric can be made from nylon, for example. The fabric and polyester layers function as a hinge between bars. The 5-bar mechanism **450** may be manufactured using 4-d printing. In another embodiment, a 5-bar mechanism may consist of 5 bars made of rigid material, with a hinge layer interposed between bars. The hinge layer may be disposed between the bars and attached to the bars using glue, mechanical fasteners, or any other appropriate method known in the arts. In some embodiments, the hinge layer **454** can be sandwiched between rigid layers **452**, **456** in order to constrain rotational motion of the 5-bar mechanism **450** to a desired axis of rotation. The rigid material can be a thin, rigid material, but other geometries can be used, provided any relatively thicker geometries do not produce interference with neighboring parts.

Briefly referring to FIG. **1** as well as FIG. **4**, the active and passive joints in the five bar mechanism **100**, such as the first passive joint **140** and the first active joint **132**, can be formed by portions of the hinge layer **454** that are not connected to the rigid layers **452**, **456**, or in other words, the portions of the hinge layer **454** not sandwiched by the rigid layers **452**, **456**. The active and passive bars, such as the first active bar **102** and the first passive bar **108**, can be formed by portions of the hinge layer **454** that are connected to the rigid layers **452**, **456**, or in other words, the portions of the hinge layer **454** that are sandwiched by the rigid layers **452**, **456**.

Referring now to FIG. **5**, various embodiments of two Degrees of Freedom (DOF) parallel mechanisms are shown. FIG. **5**A shows a mechanism **504** with five bars, one fin attachment and a plurality of water holes. FIG. **5**B shows a mechanism **508** with five bars and one fin attachment. FIG. **5**C shows a mechanism **512** with five bars and two fin attachments. FIG. **5**D shows a mechanism **516** with six bars and two fin attachments. FIG. **5**E shows a mechanism **520** with five bars and an extra angle. FIG. **5**F shows a mechanism **524** with six bars and an extra angle. FIG. **5**G shows a mechanism **528** with six bars, an extra angle, and supported hinges. FIG. **5**H shows a mechanism **532** with five bars and supported hinges. Mechanisms with an extra angle, such as the mechanisms of FIGS. **5**E-G, can avoid some mechanical singularities, which can improve performance.

Referring now to FIG. **6**, an exemplary embodiment of a pectoral fin device **600** is shown. The device **600** includes a first servo motor **604** attached to a first active bar **608** and a second servo motor **612** attached to a second active bar **616**, a first passive bar **620** in between the active bars **608**, **616**, and a fin **624** attached to a second passive bar **628**. The first passive bar **620** is also known as a ground bar because it is attached to a structural member **632** which is attached to a substrate **636** along with the servo motors **604**, **612**, and does not move, thereby coupling the first passive bar **620** to the substrate **636** and preventing movement of the first passive bar **620**. The substrate can also prevent movement of the servo motors **604**, **612**. The substrate **636** can be a portion of a body of a submersible robot such as a robotic fish. The pectoral fin device **600** is thereby coupled to the substrate **636** by the attachments to the servo motors **604**, **612**, and the structural member **632**. The submersible robot can be propelled by the pectoral fin device **600**.

Referring now to FIG. **7**, an application of a device that mimics the motion of a fish's pectoral fin is shown. A robotic fish **700** contains two pectoral fin devices (one not shown). The robotic fish **700** is a submersible robot. The pectoral fin devices are included for steering as the caudal fin is primarily for locomotion of the robot. The pectoral fin devices also may provide locomotion.

EXAMPLES

Example 1: Experimental Validation Procedure

An exemplary test for validating various designs of parallel mechanisms is disclosed. As experimental test, the Pectoral fin mechanism is mounted to a torque sensor to record and evaluate the different torque load experienced during fin's motion in water and/or under water. To this end, a plate is design to offset the fin mechanism from the sensor attachment rod. In design of the latter plate, the angle of attachment is the same with the final bar design, while the distance is increased in order to scale the forces. This is useful for increasing signal to noise ratio in force-torque sensor. Exemplary data of the collected torque values is shown in FIG. **8**. It should be mentioned that as the force-torque sensor is 6-axis sensor, it is possible to study all the generated force amounts and directions. This makes it possible to define different objectives and find the optimal maneuver for each one.

Training Algorithm

In order to find the best working regime of the fin understudy, some experimental test will be designed and accomplished. To this end, performance each working regime of the fin actuators will be validated by how much force and torque the fin generates in each directions. Based on this, different cost functions can be studied and different propulsion can be find for each cost functions. Due to usage of 5-bar mechanism, 7 parameters are defined to parameterize actuators movement. The parameters are the variables of the following formulas.

$$\beta_1+\alpha_1 \sin(2\pi t) \quad (1)$$

$$\beta_2+\alpha_2 \sin(2\pi t+\phi) \quad (2)$$

Formulas 1 and 2 are the movement of the first and second servo motors respectively. As just 10 values for each parameter will result in 10^7 tests, a smart search process is used in order to find the best working regime.

In this study an evolution strategy called Covariance Matrix Adaptation Evolution Strategy (CMAES) may be used. To this end, a Matlab code of the algorithm can be prepared. This code calls on a computer function to actuate the mechanism actuators and collecting the generated forces by fin propulsion. The computer function is created by methods know in the arts. Since the algorithm is going to be implemented experimentally, some extra pre-process items should be considered. These considerations are due to the fact that although all the parameters of actuators are independent, there is feasible range within each actuator are dependent. For example, for each actuator, not only the amplitude and offset should be smaller than the maximum moving range of the actuator (180°), their summation should also be smaller than the maximum range. In addition, the feasible range of amplitude and frequency of each servo is related to each other due to maximum moving speed of servo. Lack of considerations of these feasible ranges dependencies may result in damage to the actuators. In order to consider the latter dependencies, the parameter values estimated by CMAES is checked to meet the feasibility conditions. If a parameter is not feasible, the algorithm will return infinite as the cost value while skipping the actual experimental test. It should be mentioned that since the objective of pectoral fins implementation is to help the robotic fish with sharp turns, the cost function is selected as maximizing generated torque in z-axis direction.

Results

Referring to FIG. **9**, a five bar mechanism **900** is shown. Through the research conducted in this project, different designs for the pectoral fin mechanism were proposed, built and tested. These designs were across many different parts including rotational mechanism, servo horns, mechanism ground holder and fin designs. It should be mentioned that the final 5-bar mechanism **900** has symmetric 72 degrees joint angles. Moreover, it has a 9 layer design for strengthening the flex layer. To this end, the polyester flex layer is laminated between to fabric layers via two adhesive layers. In the final design, all the parts are aligned based on the 5-bar mechanism and the motor brackets and ground holder is 3D printed. The axis of each servo motor is aligned with the centerline of each hinge or joint. A first servo motor **904** is aligned with a first joint **908**, and a second servo motor **912** is aligned with a second joint **916**. Each servo is connected by its custom-made servo horn to its corresponding bar. This setup is shown in FIG. **9**.

Referring now to FIG. **10**, an exemplary robotic fish **1000** is shown. The robotic fish can include a body **1052** to which various components are coupled to and/or housed within. A portion of the body **1052** is shown cutaway to better depict internal components of the robotic fish **1000**. The robotic fish can include a first five bar mechanism **1004** coupled to a first servo motor **1008** and a second servo motor **1012**. The five bar mechanism can be formed with symmetric 72 degrees joint angles as shown in FIG. **9**. The five bar mechanism **1004** can be coupled to a first pectoral fin **1016**. The pectoral fin **1016** can be mounted in an upright position to the five bar mechanism **1004**. More specifically, the pectoral fin **1016** can mounted in a position to extend orthogonally away from a bar included in the five bar mechanism **1004**. In testing, this position has been shown to allow the pectoral fin **1016** to provide better maneuverability and turning radius for to the robotic fish **1000** than other mounting positions, even with the same fin design. A second pectoral fin **1036** can be coupled to a second five bar mechanism (not shown) coupled to two servo motors (not shown) and mounted to the second five bar mechanism in the same fashion as the first pectoral fin **1016** is mounted to the first five bar mechanism **1004**. A third servo motor **1056** can be coupled to the body **1052** and coupled to a caudal fin **1044** that can provide locomotion for the robotic fish **1000** as will be described below. A controller **1020** such as a microcontroller (e.g., a Raspberry Pi Zero) can be mounted to the interior of the body **1052** and be coupled to and in communication with the servo motors **1008**, **1012**, and **1056** (and the servo motors coupled to the second five bar mechanism) in order to actuate the servo motors to cause the robotic fish **1000** to move through water. In some embodiments, the robotic fish **1000** can include one or more air bladders configured to provide a certain level of buoyancy to the robotic fish **1000**. A camera **1024** can be coupled to the front of the body **1052** and be coupled to and in communication with the controller **1020** in order to record video and/or provide a live video stream to an operator of the robotic fish **1000**. The controller **1020** can include and/or be coupled to a remote communication module (not shown) capable of transmitting data using a short range communication protocol such as WiFi, Zigbee, or Bluetooth and/or a long range communication protocol such as cellular or satellite communications. The controller **1020** may be configured to receive commands and/or be piloted by an external process using instruction received from the remote communication module. A dorsal fin **1040** can be coupled to the body **1052** in order to provide stability to the robotic fish **1000** when moving in potentially turbulent waters or other extreme environments. The robotic fish **1000** propels itself by using the pectoral fins **1016**, **1036** and the caudal fin **1044**.

Due to the ease of manufacturing, the body **1052** was constructed using 3D printed polylactic acid (PLA). The fins and joint transmissions can be constructed using by laminated techniques such as the layering technique described above in conjunction with FIG. **4**. The robotic fish **1000** can achieve swimming speeds of 0.385 m/s (0.71 body length per second)-using the caudal fin **1044** and can perform pure rotation by utilizing the pectoral fins **1016**, **1036**. The turning speed in this rotation is 15.68 deg/s. The robotic fish **1000** is designed to be used in the maintenance of water canals with a width of as low as 3 feet. These canals have high currents and turbulence. In order to train the robotic fish to maneuver in this environment, a training workflow will be detailed below.

The robotic fish **1000** includes actuators have been commanded to follow sinusoidal patterns. This makes it possible to create motion with a small number of parameters, simplifying the training process. The servo motor commanding signals are defined as:

$$\text{Right pectoral fin: } \theta_1=\beta_1+\alpha_1 \sin(2\pi f_1 t)$$

$$\theta_2=\beta_2+\alpha_2 \sin(2\pi f_2 t+\phi_1),$$

$$\text{Left pectoral fin: } \theta_3=\beta_3+\alpha_3 \sin(2\pi f_3 t)$$

$$\theta_4=\beta_4+\alpha_4 \sin(2\pi f_4 t+\phi_2),$$

$$\text{Caudal fin: } \beta_5=\beta_5+\alpha_5 \sin(2\pi f_5 t) \tag{3}$$

where θ_i is actuators' angles β_i, α_i, f_i, and ϕ_i are the sinusoidal signals' angular offset, amplitude, frequency and phase shift, respectively. The angles of the servo motors coupled to the second pectoral fin **1036** are a first actuator angle θ_1 and a second actuator angle θ_2. Similarly, the angle of the first servo motor **1008** and the angle of the second servo motor **1012** coupled to the first pectoral fin **1016** are to a third actuator angle θ_3 and a fourth actuator angle θ_4 respectively. The angle of the third servo motor **1056** coupled to the caudal fin **1044** is a fifth actuator angle θ_5. There are 17 parameters to control the maneuver of the robotic fish fins. The controller **1020** can be configured to actuate the servo motors to the actuator angles θ_1-θ_5 using equation (3). The controller **17** can change at least a portion of the 17 parameters used to calculate the actuator angles θ_1-θ_5 based on a swimming mode of the robotic fish **1000**, such as turning, straight-ahead locomotion, etc.

The parameter space was searched to find optimal gaits for individual swimming criteria. While the whole space may be searched for a low-dimensional space, a covariance matrix adaptation evolution strategy (CMA-ES) technique was utilized to find ideal parameters in a high-dimensional space for which finding global optimal solutions is nearly impossible. Testing was performed to evaluate more than one top-performing gait for a given maneuver (i.e. turning, straight-ahead locomotion, etc.) using the robotic fish **1000**. The gait with consistently high-performing swimming across lab/outdoor environments can then selected for each swimming maneuver.

Turning

Being driven by the goal of maneuverability in tight spaces, a priority for the robotic fish **1000** is to minimize the turning radius. Using the pectoral fins **1016**, **1036**, the robotic fish **1000** can perform a 360-degree turn with a near zero radius. To train the robotic fish for sharp turns, a study has been carried out to maximize the amount of turning torque generated by the pectoral fin's propulsion. Turning performance has also been used as the selection criterion for selecting the fins' optimal attachment (for more details refer to material and methods section). The robotic fish **1000** achieves the best turning performance using both pectoral fins **1016**, **1036** in conjunction with each other. Two different cases were considered in the search for the best gait's parameters. In the case of simulating still water, the robotic fish **1000** is coupled to a Universal Robots UR5 robotic arm, and the UR5 is stationary; however, in the second case, the UR5 is commanded to move along a straight path at 0.1 m/s to simulate current. In both cases, the test is repeated three times for each set of parameters.

The pectoral fins **1016**, **1036** are parameterized in such a way that their motion is synchronized, but along an opposite path, meaning that when one is moving clockwise, the other one is moving counterclockwise. This is achieved by introducing following relationships:

$$\alpha_1=-\alpha_3,\ \alpha_2=-\alpha_4,\ \beta_1=-\beta_3,\ \beta_2=-\beta_4,\ f_1=f_2=f_3=f_4,$$
$$\phi_1=\phi_2 \tag{4}$$

The relationships shown in equation (4) may allow the fins' motions to magnify generated torque rather than canceling them out. This assumption also reduces the gait parameter space by half, to seven from fourteen.

Based on the peak generated torques and repeatability, 8 unique gaits were selected for testing in real-world environments by the untethered robotic fish **1000** and the best motion gait was selected based on the performance in different environments. Using the best motion gait, the robotic fish **1000** can perform a 360-degree turn with a near zero radius and the average speed of 30.25 deg/s in the two foot wide experimental setup, despite the presence of turbulence caused by waves reflected by the tank wall. It should be mentioned that the caudal fin **1044** is detached to permit the robotic fish **1000** to turn in the tank without hitting walls. During testing in a pool, the turning speed was reduced to 15.68 deg/sec, however the motion gait can allow the robotic fish **1000** to reliably turn in the pool, even when the robotic fish **1000** is subjected to turbulence. The slower turning performance of robotic fish **1000** can be mostly attributed to addition of the caudal fin **1044** and the dorsal fin **1040** on the untethered robotic fish **1000**.

For turning with a larger radius, robotic fish **1000** can utilize the pectoral fins **1016**, **1036** in conjunction with the caudal fin **1044**. While the robotic fish **1000** can use the gait selected above in combination with the caudal fin **1044** for larger-radius turning, a more energy-efficient approach is proposed to accomplish this goal. In this approach, the pectoral fins **1016**, **1036** are commanded to move to different fixed configurations, producing different drag forces. This asymmetric drag on the body **1052** enables the robotic fish **1000** to turn gradually, while saving power by avoiding continuous actuation of the pectoral fin servos. As the objective is to find the configuration that maximizes turning torque at various speeds, individual tests are repeated three times per parameter set, once at 0.1, 0.2, and 0.3 m/s each. The cost function has been defined as the summation of average turning torque generated across all three speeds.

Swimming Forward

A series of studies have been run to improve the forward thrust generation and swimming speed of the robotic fish **1000** by finding the best gaits for both the caudal fin **1044** and the pectoral fins **1016**, **1036**. The next sections discuss several approaches for maximizing swimming speed, including minimizing body drag, optimizing the caudal fin gait, and learning whether the pectoral fins **1016**, **1036** can contribute to thrust generation as well as for turning. Since a force-torque generation evaluation has been developed as the criteria for robotic fish performance, each study measures the amount of forces applied to the body **1052** of the robotic fish **1000** at different speeds using the experimental setup. This measurement enables us to understand the swimming performance of the robotic fish when moving freely. Body drag is measured by commanding the robotic arm to travel the tank length at a number of fixed speeds and at each speed, the average drag force on the body **1052** is sampled. It should be mentioned that in this test, all fins are in their neutral configuration ($\alpha_i=\beta_i=0$).

Body Drag Minimization

The pectoral fin configuration affects the amount of drag exerted on the robotic fish. The training algorithm has succeeded to reduce the sum of drag to 60 percent across different speeds by finding the optimum configuration of the pectoral fins **1016**, **1036**. The obtained results showed that the summation of drag value across all speeds has been reduced from 2.5N in neutral state to 1.5N in minimum-drag state. In order to minimize body drag, the training algorithm can be used to minimize drag by finding fixed servo positions that put both fins in an orientation that minimizes drag. The objective is to find the configuration that produces minimum drag across various speeds that the caudal fin **1044** can realistically achieve. Individual tests are repeated three times per parameter set, once at 0.1, 0.3, and 0.6 m/s each. The cost function has been defined as the summation of average drag exerted on the robotic fish in all mentioned speeds.

Forward Thrust Generation with the Caudal Fin

The robotic fish **1000** can swim forward with the maximum speed of 0.385 m/s by relying solely on the caudal fin **1044**. This mechanism consists of a servo motor moving a flexible, fin-shaped plastic sheet back and forth to produce thrust. Experimental results show that the tail performs best when α_5=60 deg and f_5=1.4 Hz. The thrust produced by the caudal fin **1044** is controllable when f_5=1.4 Hz. Hence, the motion of the caudal fin **1044** is therefore set to be symmetric ($\beta_5=0$). The three-dimensional space of function parameters (α_5, β_5, and f_5) has been spanned by measuring the average of sampled thrust produced by the caudal fin **1044** across one cycle. Two different cases of pectoral fin orientations have also been considered throughout the caudal fin study. These cases are neutral and minimum-drag orientations of the pectoral fins **1016**, **1036**. The maximum thrust produced by the caudal fin **1044** increases by almost 15 percent when the pectoral fins **1016**, **1036** have been moved from their neutral to the minimum-drag configuration. After fitting drag and thrust generation plots, it was estimated that the caudal fin **1044** can achieve a forward velocity of 0.16 and 0.18 m/s when the pectoral fins **1016**, **1036** are in their neutral and minimum-drag configurations, respectively. Considering that the robotic fish has attachments that increase drag during laboratory experiments, the swimming speed achievable by the un-tethered robotic fish is expected to be more than the value that has been estimated by matching the body drag and the thrust generation of the caudal fin **1044**.

Forward Thrust Generation with Caudal and Pectoral Fins

The purpose of this next study is to improve forward thrust by utilizing the propulsion of the pectoral fins **1016**, **1036**. The obtained results show that in the current design and configuration, the pectoral fins **1016**, **1036** are not capable of improving the thrust produced by the caudal fin **1044**. Different cases have been considered for this objective. In the initial case, an unconstrained full search was performed. This has resulted in a gait search in the 16-dimensional parameters space (two for symmetric caudal fin propulsion and two sets of seven variables for each pectoral fin). In this test, the UR5 moving speed is 0.1 m/s. The obtained results showed that the training algorithm did not converge after one hundred iterations. Considering that on average, each iteration takes a hundred minutes, the study has not been carried out for more iterations. Instead, some simplifications have been applied to help the training algorithm to converge. The caudal fin **1044** has been set to produce maximum forward thrust and the pectoral fins **1016**, **1036** have been commanded in a way that they have symmetric propulsions. This is achieved by introducing following relationships:

$$\alpha_1=\alpha_3,\ \alpha_2=\alpha_4,\ \beta_1=-\beta_3,\ \beta_2=-\beta_4,\ f_1=f_2=f_3=f_4,\ \phi_1=\phi_2 \tag{5}$$

For each set of parameters, the test is repeated three times while the UR5 moving speed is set to 0.1 m/s. The obtained results showed that all tested gaits have values less than the thrust achievable by the caudal fin **1044** alone. Finally, another case has also been studied to evaluate the ability of the thrust generation of swimming with the pectoral fins **1016**, **1036** with the caudal fin **1044** disabled. The highest performing gait is only capable of overcoming the body drag of the robotic fish **1000** when the UR5 is commanded to move the fish at 0.1 m/s speed. This result shows that the symmetric propulsion of the pectoral fins **1016**, **1036** can produce only limited forward thrust in certain circumstances; the maximum speed achievable is around 0.1 m/s.

Referring now to FIG. **10** as well as FIG. **11**, a process **1100** for controlling actuators coupled to parallel mechanisms and/or caudal fins in a robotic fish is presented. The process **1020** can be stored as instruction on a memory included in or coupled to the controller **1020** and executed by one or more processors included in the controller **1020** in order to control components of the robotic fish **1000** described above.

At **1104**, the process can determine a swimming maneuver. The swimming maneuver can be forward swimming or turning. The process **1100** may receive a command indicative of the swimming maneuver from a remote source via the remote communication module described above. The swimming maneuver can be predetermined. The process can then proceed to **1108**.

At **1108**, the process **1100** can determine optimal parameters for the swimming maneuver for the first servo motor **1008**, the second servo motor **1012**, the third servo motor **1056**, and the two servo motors coupled to the five bar mechanism coupled to the second pectoral fin **1036**. The process **1100** can access predetermined optimal parameters such as the angular offsets, amplitudes, frequencies and phase shifts included in equation (3) above that correspond to the swimming maneuver. Different maneuvers may have different optimal parameters. The process **1100** can then proceed to **1112**.

At **1112**, the process **1100** can calculate a pattern for providing angular positions to the servo motors using equation (3). Using the optimal parameters, the process **1100** can calculate a series of angular positions (θ_i in equation (3)) for a number of time points. The pattern can be sinusoidal. The process **1100** can then proceed to **1116**.

At **1116**, the process **1100** can actuate the servo motors based on the pattern. The process **1100** can actuate the servo motors to the angular position specified by the pattern at each time point and cause the robotic fish **1000** to turn, swim forward, etc. The process **1100** can then end.

The present invention has been described in terms of one or more preferred embodiments, and it should be appreciated that many equivalents, alternatives, variations, and modifications, aside from those expressly stated, are possible and within the scope of the invention

We claim:

1. A device for providing propulsion in water, the device comprising:
- a parallel mechanism comprising at least five rigid bars and at least five joints, each joint being positioned between two of the rigid bars and configured to allow movement of the at least five rigid bars;
- a first servo motor coupled to a first rigid bar included in the at least five rigid bars;
- a second servo motor coupled to a second rigid bar included in the at least five rigid bars; and
- a controller coupled to the first servo motor and the second servo motor and configured to actuate the first servo motor and the second servo motor according to a predetermined pattern.

2. The device of claim **1**, wherein the at least five joints are evenly spaced around the parallel mechanism.

3. The device of claim **1**, wherein the at least five joints comprise a fabric.

4. The device of claim **1**, wherein the predetermined pattern includes a sinusoidal pattern.

5. The device of claim **1**, wherein a third rigid bar included in the at least five rigid bars is coupled to a substrate, the third rigid bar being positioned between the first rigid bar and the second rigid bar, and wherein the first servo motor and the second servo motor are coupled to the substrate.

6. The device of claim **5**, wherein the third rigid bar is attached to the substrate via a structural member.

7. The device of claim **5** further comprising a fin attached to a fourth bar of the at least five rigid bars and extending orthogonally away from the parallel mechanism, the fourth bar positioned adjacent to the first rigid bar, and the fourth bar moving when the first rigid bar moves.

8. The device of claim **1**, wherein the pattern is determined based on predetermined parameters corresponding to a swimming maneuver, and wherein the predetermined pattern comprises a series of angular positions for the first servo motor and the second servo motor.

9. The device of claim **1**, wherein the device is included in a robotic fish.

10. The device of claim **1**, wherein the at least five joints comprise nylon.

11. The device of claim **1** further comprising a fin coupled to a third rigid bar included in the at least five rigid bars.

12. The device of claim **11**, wherein the fin is configured to provide a turning force to a submersible robot.

13. The device of claim **11**, wherein the fin is configured to provide a locomotion force to a submersible robot.

14. A robotic fish comprising:
- a parallel mechanism comprising at least five rigid bars;
- a first servo motor coupled to a first rigid bar included in the at least five rigid bars;
- a second servo motor coupled to a second rigid bar included in the at least five rigid bars;
- a fin coupled to a third rigid bar included in the at least five rigid bars; and
- a controller coupled to the first servo motor and the second servo motor and configured to actuate the first servo motor and the second servo motor according to a predetermined pattern in order to provide a turning force to the robotic fish.

15. The robotic fish of claim **14**, wherein the parallel mechanism comprises at least five joints, each joint being positioned between two of the rigid bars and configured to allow movement of the at least five rigid bars.

16. The robotic fish of claim **15**, wherein the at least five joints are evenly spaced around the parallel mechanism.

17. The robotic fish of claim **15**, wherein the at least five joints comprise a fabric.

18. The robotic fish of claim **14**, wherein the predetermined pattern includes a sinusoidal pattern.

19. The robotic fish of claim **14** further comprising a caudal fin coupled to a third servo motor, wherein the controller is further coupled to the third servo motor and configured to actuate the third servo motor in a second predetermined pattern in order to provide a locomotion force to the robotic fish.

20. The robotic fish of claim **14**, wherein the fin extends orthogonally away from the parallel mechanism.

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 11,124,281 B2
APPLICATION NO. : 16/655018
DATED : September 21, 2021
INVENTOR(S) : Daniel Aukes et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

Column 9, Line 39, "angles β_i" should be -- angles and β_i --.

Signed and Sealed this
Thirtieth Day of November, 2021

Drew Hirshfeld
Performing the Functions and Duties of the
Under Secretary of Commerce for Intellectual Property and
Director of the United States Patent and Trademark Office